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Final Report

Optical System Design for the Next Generation Space Telescope

17 October 1996

by

Leonard H. Solomon
Principal Investigator

SolVisions
82 Albemarle Road
Norwood, MA 02062

and

Mark A. Kahan
Optical Research Associates, Inc.
East Coast Office
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NASA/MSFC Order # H-26700D

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NGST OPTICAL SYSTEM STUDY

SolVisions, supported by Optical Research Associates (ORA®), is pleased to have been a part of the NASA/MSFC team developing the initial design concepts for the Next Generation Space Telescope. SolVisions and ORA staff have been supporting technology development and system design for large telescope systems for space since the initial design studies for HST, performed by the same Investigators with Itek Optical Systems, for NASA Headquarters, beginning in 1969.

Over the past few years SolVisions and ORA have each worked on a very broad range of deployable telescope topics and demonstration hardware. Based on that work, much of it done on Itek programs sponsored by the Government, SolVisions has provided data in this report on deployable telescope design, and on deployable primary mirror technology, specifically suited to their system implementation for high performance operation in space. Our recommendations for technology development supporting the NGST are included.

Much of the ORA work is based on proprietary data and spans disciplines ranging from classical optical modeling and tolerancing using CODE V® and LightTools® through to opto-mechanics, thermo-optics, material science, and parametric cost/weight modeling. A brief data package was provided for NASA use on April 15, 1996, addressing some of these areas. The ORA section of this report expands upon the earlier briefing in the areas of thermo-optics, materials, and system natural frequency; tying these to both cost and weight. Much remains to be done, of course, but these initial looks show the cost goal ($10M for an 8-m primary) to be aggressive, though rational, while a weight goal of 10-12kg/m^2 is about a 15-30% stretch of the state-of-the-art..

Both SolVisions and ORA wish to thank the remainder of the NASA IPT for their continued support and interaction, and we especially appreciate the efforts of Max Nein and James Bilbro.

NGST Report

Charts Provided:

Optical Design Considerations

General comments are provided here on the issues to be addressed in developing an adequate optical design for NGST. The IPT baseline, as of August, 1996, is responsive to these needs, and approximates the extrapolated ALOT design we originally suggested at the April, 1996 meeting for use in the NGST.

Optical Design Considerations

An NGST optical design should provide:

Adequate focal length to provide spatially resolved images at focal plane instruments (spectrometer, photometer, etc.)

Acceptable scale image of primary at a (flat) deformable mirror for wavefront control

Location for fast steering mirror for image motion control

Provision for light baffling

- IPT Baseline - Nearly-centered three-mirror reflective design can meet all criteria

Configuration Choice

Previous studies, some for classified system applications, have evaluated the relative utility of various forms of filled and unfilled aperture for remote sensing. In general, although a large aperture can yield high ultimate resolution, a low fill factor leads to low MTF and therefore (for any achievable sensor Signal to Noise ratio) great difficulty in reconstructing the imagery to obtain the information content consistent with the predicted high resolution based on the aperture. For low aperture fill factor, especially for azimuthally varying cases, the situation is even more pronounced in the use of non-imaging instruments, whose observing efficiency is degraded by the lack of contrast between target objects and sky background.

We strongly recommend the use of a filled aperture system.

Configuration Choice

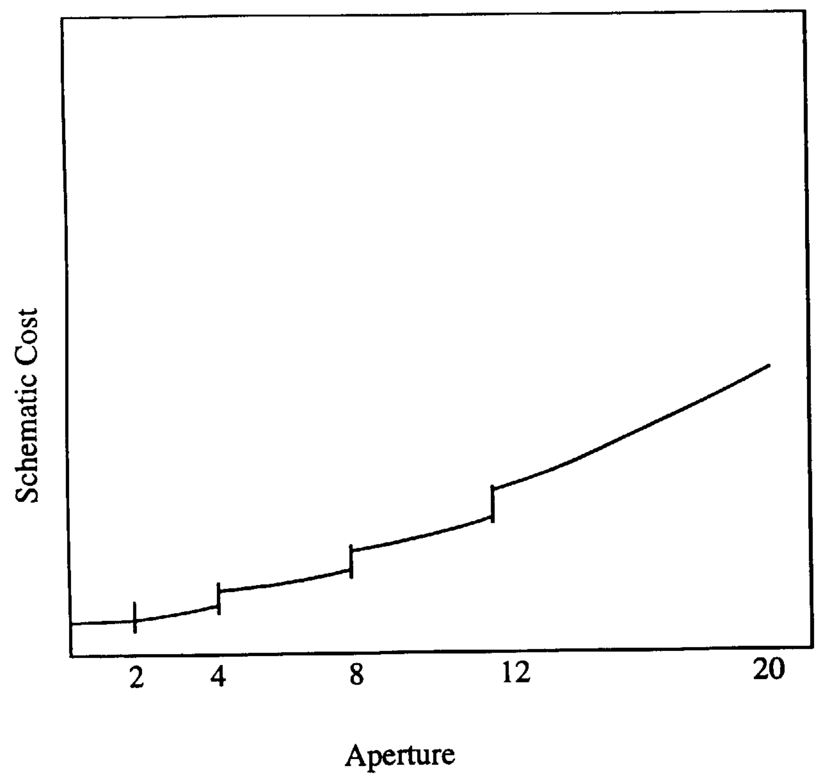
Various studies of large unfilled apertures have determined, both analytically and experimentally, that the most useful primary mirror configurations for imaging and especially for energy detection devices (photometers and spectrometers) are annular or filled apertures, due to their monotonic, relatively high MTF response.

Unfilled aperture configurations, even the Golay-6 and Golay-9 forms, do not allow straightforward image reconstruction with achievable signal to noise from the imaging device.

Aperture Breakpoints

In considering the development of NGST apertures from 2.5 meters to 20 meters, technology and engineering issues combine to indicate significant breakpoints in the relative difficulty, risk and cost of delivering a system to operational status on orbit. For example, the existing facilities suitable for production of high quality Be and SiC mirror facesheet blanks are limited to 1 - 2 meters aperture. Should one of those materials be required, unless other users are found to share the capital cost, the mirror cost must be increased by the cost of design, installation and qualification of the large-scale facilities required. Other materials, such as the low-expansion glasses, which have been previously demonstrated to provide the NGST-required performance in large mirror segments, do not require new facilities until 4 - 5 meter segment apertures are required. Therefore, at 2 meters, the slope of cost vs. aperture increases, but there is no discontinuity until 4 meters size is reached. Further, at 4 meters, the size of the launcher clearly requires use of a segmented mirror, whereas a monolithic primary might be usable below 4 meters. The discontinuity is also based on the incremental cost of the on-board deployment and phasing control system. From 4 to 8-m aperture, the slope of the cost curve is similar to that between 2 and 4-m, since the multiple segments will lie in the 2 - 4-m range. At 8-m, the existing choice of launcher limits the system aperture; beyond 8-m a larger launch vehicle and shroud are required, at a large incremental cost. When the 11 - 12-m size is reached, either the segment size must be increased from 4-m, or a multiple ring approach (and therefore some scheme other than simple fore-and-aft foldout) is needed for deployment. Either of those mirror approaches causes another large discontinuity in facility cost and scale-up risk.

System Considerations
Aperture Breakpoints - Near Term Technology



- 1 - 2 meters is current limit for Be and SiC mirror blanks - facilities limit
- 2.5 meters is facility limit for ion figuring, existing CCOS facility limit is ~4 meters, "conventional" polishing to 8 meters
- 4 meters is composite mirror size limit using lightweighted glass facesheets- facilities limit
- 8 meters is packaging limit for Atlas shroud based on weight and volume for 3-4 m mirrors
- 11-12 meters is size limit for simply-deployed system based on 4-m mirror panels
- Can achieve up to 20 meters with double row of outer panels of 4-m scale, requires pick and place mechanism to assemble

Telescope Technology Limitations
Deformable Mirror

Limits on the telescope configuration choices are also set by component technology limits for critical elements of the design. One such case is the pupil (deformable) mirror. Areas of likely development or demonstration needed for this device include the stroke achievable at 30K, and the combination of stroke and actuator count available in a mirror of the 6 to10 cm size dictated by the baseline optical design. In the smallest size, actuators would be required at a spacing one-half that currently used to provide the NGST-required 4 μm stroke.

Technology Limits on Telescope
Deformable Mirror

Critical Issues

Actuator Spacing/Stroke/Influence Function
Low temperature DM operation

Impact on System Design

Actuator spacing affects minimum size of pupil mirror, based on scale of residual WFE to be corrected, for a given actuator count. This could limit choice of focal ratio. Current baseline configuration would require 3.5 mm actuator spacing.

If 30K operation of DM cannot be provided, existing technology would require heating the DM, or direct correction of primary mirror panels, to provide correction of WFE.

Existing Technology

Stroke of ~4μm is produced by existing combination of device parameters, including actuator spacing of 7 mm. Other parameters include actuator diameter and length, facesheet thickness, voltage, etc. To achieve 4mm stroke with closer spaced actuators will require engineering development of materials and processes.

Electrostrictive material used for actuators is limited in low temperature response, demonstration required for 30 K operation.

Low Temperature Mirrors
Technology Issues

For composite primary mirror segments, another limit on design is due to differences in coefficient of thermal expansion (CTE) between the mirror components, and local CTE non-uniformity, particularly facesheet and substrate. A large difference, at fabrication or operational temperature, or during the cooldown cycle, can cause sufficient strain in the materials to impair the structural integrity of the units, or to degrade the response of the mirror face to actuation, if calibration is done for one temperature and operation is at another. These CTE issues impose a requirement to test mirror surface quality at operational temperature, and in the likely event that there is a large thermally-induced wavefront error, a surface error map must be made, then corrected at room temperature, before retest at the low temperature. Finally, since the deployment and phasing mechanisms must also operate at low temperature, the complete mirror should be tested at 30K, thus requiring a large thermal-vacuum chamber, instrumented for optical test, operating efficiently at that temperature.

Low Temperature Mirrors
Technology Issues

<u>Major Drivers</u>

Material selection

- CTE and CTE uniformity of facesheet for 250K difference between fabrication and operational temperatures
- CTE match between substrate and facesheet over temperature range
- Calibrated operation of actuators (mirror segment or pupil mirror) at operational temperature

Fabrication and Test

- Mirror segments must be tested at operational temperature, but any fabrication errors removed at ~290K.
  Facility and test process significant issues
- Full primary mirror and system test at operational temperature will be major cost driver, if facility and test are feasible at all

Composite Primary Mirrors

Composite, segmented large mirrors have been developed for several purposes under ARPA and other Government funding, and this chart shows some of the results of that work. The performance goal for the High Altitude Large Optics (HALO) program was consistent with Near-IR sensor operation, with a 10-m aperture. The specific data describe equipment made and demonstrated in the early 1980s. These form the backdrop for later development for other programs, and for possible low-risk design approaches for NGST.

Composite Primary Mirrors

Technology Base- HALO Optics Technology (& other programs)- 1978 to 1986

Overview- Designed for 1/10 wave visible performance, for cold Vis/Near IR system
Demonstration based on 3-m aperture, to show feasibility of 10-m class segmented cryo systems
System operated at full performance at ~100K, critical items fully tested at 77K, some to 10K (for SIRTF)

Mirror Configuration- Lightweighted glass facesheet, supported by force actuators from Gr-epoxy substrate
Fabricated mirror size (2 made) 1 x 2.5 m, near-annular - area 2 m^2 each, 1x1-m first made as demo

Some details on construction - Total Mass/Area ~24 kg/m^2 (as measured in 1984 demo unit)

HALO Facesheet: Fused silica (CTE ~ 0 @ 60K), ~25 mm depth, square lightweighting pattern ~50 x 50 mm
Wall thickness - 2.5 mm (nominal), Face thickness - 2.5 mm (nominal) Variation ~±25 μm
Edge band (2 cm wide) not cored
Actual mass/area ~14 kg/m^2

HALO Actuators: Small Kimco stepper motor, threaded shaft/nut, spring, graphite-epoxy tube assembly
Epoxy bonded to facesheet using Invar flexure/glass "button" assembly attached to gr-ep tube
Mechanical attachment to substrate used a self-centering Be-Cu radial flexure at each substrate face
45 (@ 0.23 kg) used for each large mirror, including wiring
Actual mass/area ~ 5 kg/m^2

HALO Substrate: Graphite-epoxy, low expansion, CTE-match to fused silica lightweight semi-monocoque
Depth ~ 0.1 m; face-, backsheets provide inserts to mount actuator BeCu radial flexures and motors
Actual mass/area ~ 5 kg/m^2

Composite Mirrors
Technology Improvements

A late 1980s demonstration program, known as ALOT, extended the performance requirements to the visible, and required system operation in a highly dynamic, long-life environment. Therefore, the ALOT design emphasis was on low risk and high stiffness, rather than on low weight. Materials were improved, and all items were engineered and tested for flightworthiness, but the weight regime achieved was no better than HALO. Another demonstration, known as LOS, achieved 4-m dimension optical surfaces (center and edge panels of a 10-m class mirror), whereas ALOT provided 2.7-m in a center segment and a smaller outer panel. ALOT demonstrated full segmented mirror initialization, and both phasing and optical surface control over many months, using external reference sources.

Historical Composite Mirror
Technology Refinements

<u>For ALOT and other programs - (late 1980s-1994)</u>

ALOT Overview- Designed for Visible, high performance, low-risk operation, high dynamic environment
Demonstration glass facesheets included 2.6-m center and 1 outer panel (of 6) of a 4-meter mirror
These were mounted to a very deep, stiff Gr-epoxy substrate/optical bench via dual range actuators
All electromechanical and electronic items were designed with redundancy to be flight-qualifiable

NOTE: Overall system not designed to minimize weight, therefore many features unsuitable for NGST

Facesheet: ULE, depth 40 mm, lightweighting pattern equilateral triangles with 200mm sides
Wall and facesheet thickness increased to 3 mm, but variation reduced to ± 2.5 µm
Edge pattern same as remainder of facesheet. Stiffness equivalent to 17 mm thick solid meniscus

Mass/area reduction - modest at best

Actuators: Due to introduction of redundancy, harmonic drive and addition of PMN fine resolution stage, weight per unit increased to 0.45 kg.
Changes not necessarily applicable to NGST

Substrate: Designed for very high resonant frequency, and to serve as support for other system elements
Very deep structure, not applicable to NGST

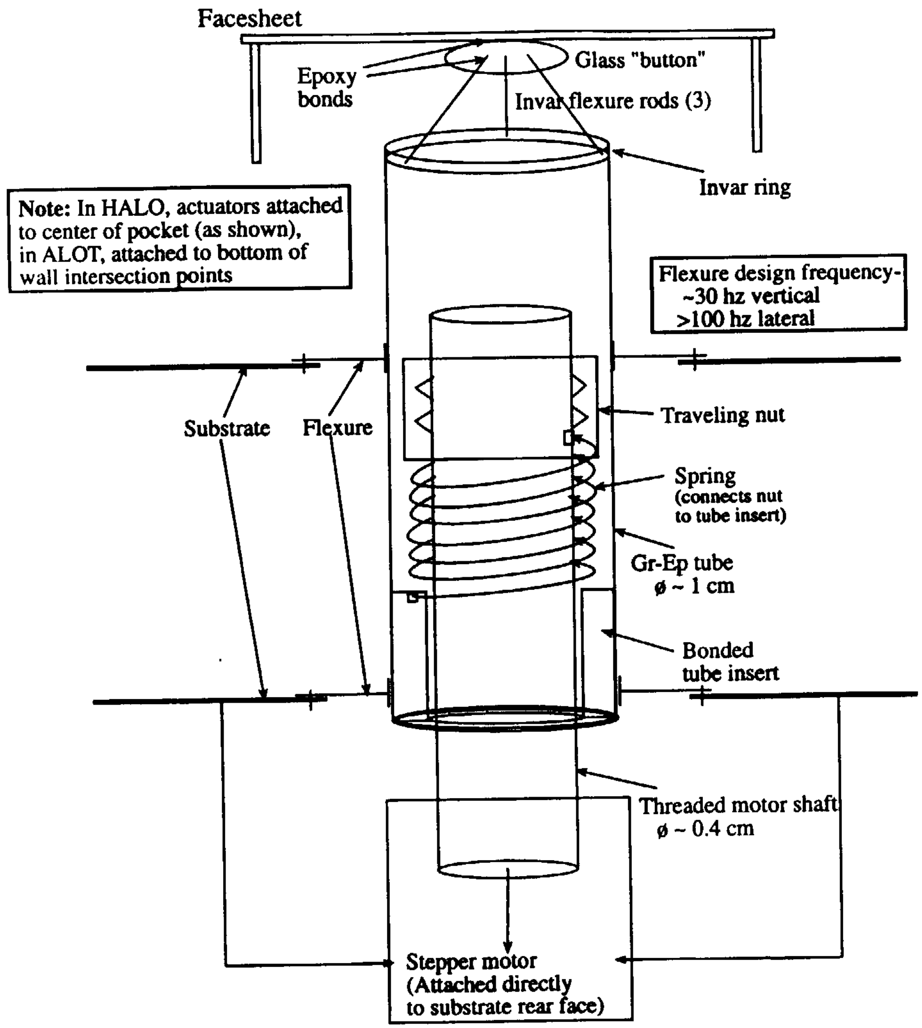
Legacy to NGST- Demonstrations of initial mirror phasing, independent control system operation using external reference source, long-term phasing stability and update capability.

LOS Demonstration: Surface fabrication of center and outer 4-m segments of 10+-m deployable mirror
These 17-mm thick segments not lightweighted due to system application
WFE at completion met specification, suitable for NGST needs

Composite Mirror
Schematic Configuration

The HALO-derived composite mirror configuration is schematically shown, based on the actuator as the focal point of the sketch. The lightweighted glass facesheet and semi-monocoque graphite-epoxy substrate are noted in passing, but their physical design has not changed much from HALO to the most recent designs for composite mirrors. The facesheets were of a "pocketed" construction. with both hard machining and chemical milling techniques used to achieve thin, precisely dimensioned walls and facesheets. The substrate was designed to be stiff and lightweight, and to accommodate he actuators which in turn support and control the operational shape of the facesheet. In the HALO program, the successful final telescope performance demonstration was done at 100K.

Composite Mirror
Actuator Schematic Configuration



- Actuator and placement shown for HALO configuration
- Note indicates placement of actuator attachment for ALOT
- ALOT used PMN stack at glass attachment point to provide large stroke with high precision
- Weight of HALO device ~ 0.24 kg
- Weight of ALOT dual range unit, including redundancy ~ 0.45 kg
- Low temperature lubricant used for 77K-qualified HALO actuators was Molybdenum Disulfide Vespel

Future Composite Mirrors

Based on the HALO, ALOT, LOS and other programs, the composite mirror design configuration is extrapolated here for application to NGST. This chart shows both glass and SiC facesheets applied to the design, with their different stiffnesses leading to a difference in spatial distribution of the actuator supports. While the weight predictions are not definitive, requiring further validation from structural model analyses, they should be representative of a low-risk design.

Future Composite Mirrors

Projected weight reduction using Conservative technology improvement

Concepts configured for nominal constant performance of HALO mirrors - 1/10 wave vis/NIR

Component/Technology (Existing)	HALO	NGST-A	NGST-B
Facesheet:			
Material	Glass 25 mm deep, 50 mm sq cores 2.5 mm walls, faceplate	Glass 25 mm deep, 200 mm triang. cores 2.2 mm walls, faceplate	SiC (closed back) 15 mm deep 200 mm triang. cores 0.75 mm walls, 2 mm faceplates
Mass/Area (kg/sq m)	**~14**	**~11**	**~ 8**
Actuators:			
Assume HALO units	~22/sq m	~22/sq m	increase spacing ~15/sq m
Mass/Area (kg/sq m)	**~ 5**	**~ 5**	**~ 3.5**
Substrate:			
Material	Gr-epoxy, 0.1 m deep Lightweight, 2 faces	Gr-Cyanate Current COI config	Gr-Cyanate Current COI config
Mass/Area (kg/sq m)	**~ 5**	**~ 4.5**	**~ 4.5**
Total Mass/Area (kg/sq m)	**~ 24**	**~ 20.5**	**~ 16**

Improved Composite Mirrors

The following further potential improvements in weight for the composite mirror still use the glass and SiC facesheets, but the weight predictions are based on operationally achieving the limits of fabrication performance projected from the prior development programs. Routinely achieving these parameters for NGST, including the mass/area ratio of the mirrors, will require substantial technology work, especially in scaleup of processes.

Improved Composite Mirrors

Further Potential Weight Reductions

Overview: Apply only improvements producing significant weight reductions

Component/Technology (Existing)	**HALO**	**NGST-A**	**NGST-B**
Facesheet:			
Material	Glass	Glass	SiC (open back)
	N/A	2.0 mm walls, faceplate	20 mm deep, 1 mm walls, 2 mm faceplate
Δ Mass/Area (kg/sq m)	**0**	**- 1**	**- 2**
Actuators:			
Replace by springs (30 hz vert, >100 hz lateral)	~22/sq m	~22/sq m	~15/sq m
Mass/Area (kg/sq m)	**N/A**	**- 2.5**	**- 2**
Substrate:			
Material	Gr-epoxy, 0.1 m deep no change	Gr-Cyanate Current COI config	Gr-Cyanate Current COI config
Mass/Area (kg/sq m)	**0**	**0**	**0**
Total Mass/Area (kg/sq m)	**~ 24**	**~ 17**	**~ 12**

Primary Mirror Segment Surfacing

Surfacing of odd-shaped mirror segments of 3- to 4-m aperture is not an ordinary optical shop procedure, especially for segments that must be close-packed and phased in operation, which require closely matched focal lengths. Of the available processes that could do the work, only Computer Controlled Optical Surfacing (CCOS) has been proven at these mass-area ratios and sizes, although with some development and/or facility improvement each of the others would probably be acceptable as well.

Primary Mirror Segment Surfacing

Results required:

- **Aspheric surface, several hundred λ from nearest sphere**
- **0.03 μm rms or better surface error**
- **precisely matched f/1.25 figure (focal length) on segments**
- **8 - 12 Å surface roughness or better, no residual print-thru**
- **finished to very edge of lightweight facesheet surface**
- **cryo temperature operation**

Mirror surface material- Fused Silica, SiC, Be (HIP) or other metal

Potentially available surfacing techniques

Conventional loose abrasive operation, post cutting

Ion figuring

CCOS- special lap control

Replication

- **CCOS has demonstrated all requirements, though not all at once; facilities available to 4 x 6 meters capacity**

Primary Mirror Technology Base
Composite Mirrors - Glass Facesheet

This chart shows a tabulation of the attributes or features required for the NGST segments or mirror assemblage, and references one or more prior programs (performed at Itek) during which this specific requirement was addressed. Based on this history, it is asserted that the large, segmented, lightweight mirror represents a problem of relatively contained risk.

Primary Mirror Technology Base
Composite Mirrors - Glass Facesheet

Attribute/Feature	Tech Demo Program (at Itek)
Segment Fab (Non-circular shape)	HALO, LAMP, ALOT, LOS
4-m size (Facesheet, substrate)	LOS, ALOT
Surface quality	ALOT, LOS, MATS, 8105
f/1.5 or faster	ALOT, LAMP, LOS
Full surface figured (<3mm to edge)	ALOT, 8105
Ultra L/W facesheet	HALO, LPMA, ALOT, ULM,
Matched figure (radius)	LAMP, ALOT, 8105
Edge phasing (absolute)	LAMP, ALOT
Large SiC fabrication (1.1 x 0.9 m)	SiC Demo (AOMP)
Surface roughness (10 - 15Å)	ALOT, 8105, LPMA, SiC
Cryocycle of mirror assembly	HALO (105K), SiC (135K), Teal Ruby

Partition of Functions
Wavefront Control System

Active control of optical systems may be achieved in various ways. However, it is possible to design the control architecture in ways that take advantage of existing technology, or at least minimize the requirements on new development. One specific area is that of egment phase error correction, which could be done at a pupil mirror, but which would require high local slopes at the segment edge locations, well beyond any such requirements on the remainder of the mirror. It would therefore be prudent to perform that control function directly at the primary, leaving the residual wavefront error at a size commensurate with local mirror surface errors.

Partition of Functions
Wavefront Control System

Panel Phasing- Due to the large potential local slope implied in a deformable pupil mirror if this function were done at an image of the primary (i.e., several waves height difference in one spatial frequency cell), panel phasing control should take place at the primary mirror panels themselves. To achieve this control at the pupil mirror would require an additional element of technology development, beyond that already required. On the other hand, panel phasing has already been demonstrated for segmented mirrors in such development/demonstration programs as HALO, LAMP and ALOT.

Mirror Segment Wavefront Error Control- Wavefront errors caused by environmental effects or residual fabrication errors may be corrected at either the mirror surface or at a pupil mirror, whichever is more convenient. Such correction has been experimentally demonstrated using both approaches, in the HALO, LAMP and ALOT demonstrations, and the various Atmospheric Compensation programs. For NGST, where weight is a critical issue, lighter system weight may be achieved by use of a pupil mirror, should the actuator weight not be required as part of the primary mirror structure.

Alignment-Induced WFE- Should normally be controlled by actively maintaining proper alignment of the optical surfaces.

Line of Sight Control

Line of sight control is another system control function that has been addressed in many previous systems, both space- and ground-based. This chart indicates a range of approaches, implemented in prior equipment, that can probably be used in an overall control algorithm to perform LOS control of NGST to the required 0.005 arcsec level.

Line of Sight Control

Sources of LOS Disturbance

- Slew dynamics
- On-board equipment and component response dynamics (CMGs, Coolers, Sunshade/Solar panel clocking, etc.)

Issues in LOS Stabilization

- Isolation of disturbance sources
- Improving effective stiffness and damping of structure (particularly secondary mirror support)
- Use of active LOS control measures

Technology Available

- Passive and active isolation of disturbance sources
- Active damping of structural elements
- Secondary mirror fine pointing control
- Fast steering mirrors
- Distributed system control architecture

General note: Design and implementation of LOS control for NGST is a challenging engineering task, whose solution depends on proper design and allocation of control functions, rather than new technology development.

NGST OPTICAL SYSTEM ENGINEERING TRADES

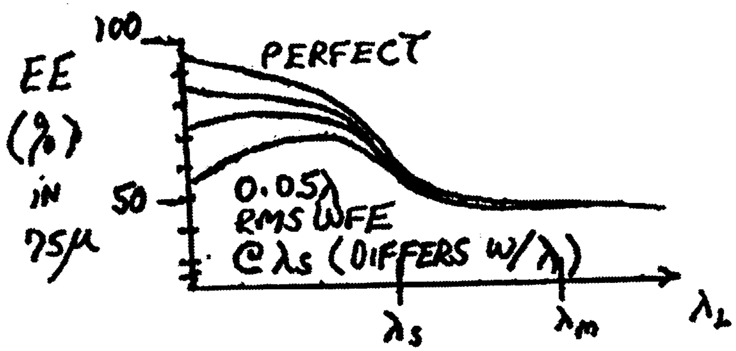
We have begun work on parametric modeling of various performance measures. This helps us understand how the science objectives of the mission can drive both weight and cost. One specific example is shown here.

Let's assume that we wish to distinguish a dim "small" object. We first estimate the aperture needed to collect sufficient light for our jitter and drift limited exposures and what size pixel is likely to be at the state-of-the-art for the anticipated detectors of tomorrow. Since we'd like our telescope to efficiently use the energy it collects, we wish to configure our Airy disk diameter to fall within a pixel. We can do this by varying both f-number (i.e., focal length for a given aperture size) and wavelength of operation (l), accounting for the influence of tolerances as part of the process.

This figure shows some of the parametrics involved. In this case we assume our pixel size has been selected and an f-number chosen, based on factors including packaging and tolerance sensitivity. Some of these factors also tie to wavefront error (WFE), so the optimization process is somewhat iterative in terms of which combination of f-number, l, and WFE give the lowest cost. Here we can see that as l increases, the impact of WFE becomes less important (as we are measuring our error with a longer "ruler") until the effect of diffraction takes over and the energy in a pixel falls off due to the increased spot size. This type of study is useful in that it lets us quantify how the shortest wavelength of operation (l_s) directly sets allowable WFE (for a given f-number, pixel size, and S/N or ensquared energy/EE). This allowable WFE in turn directly ties to tolerances, weight, and cost.

NGST OPTICAL SYTEM ENGINEERING TRADES

- Performance parametrics are in work
- Determine how performance varies as a function of wavelength for
  - Residual / Higher Order Wavefront Error
  - Residual Defocus
  - Jitter



- As λ's ⇑ => • WFE Effects ⇓

  Eventually Diffraction Governs

- Pixel sizes will evolve over time so run for expected state of the art/based on launch date
- Establish adjudicated tolerances and degrees of freedom (adjustments) balancing against cost (by item)

COST & WEIGHT MODELING ARE KEY PARALLEL EFFORTS

We have found that by taking detailed error budgets and translating each error term into what the specific tolerance of interest means to cost and weight, we can often revise or reapportion the error to maintain performance but reduce weight and/or cost. This type of analysis helps us understand/ease "hidden" factors and pro-actively design-to-cost rather than accept self-fulfilling prophecies based on schedule and/or team size. We have used this WFE and natural frequency (F_N) driven parametric approach to compare technical alternatives and establish cost-and-weight optima for both design form and the placement and type of adaptive controls. In some of our prior work we were able to hold performance while simultaneously lowering both weight and cost to ~25% of their initial values.

COST & WEIGHT MODELING ARE KEY PARALLEL EFFORTS

- Objective:
  - Provide Cost & Weight Data $\Rightarrow$ Compare Technical Alternatives
  - Specific Attention to Design Form and Adaptive Aspects
    - Residual RMS Wavefront Error (RMS WFE)
    - Natural Frequency (F_N)
- Work Break-Point Parametrics-Avoid Self Fulfilling Prophecies
  - Understand / Ease "Hidden" Costs
  - Revise / Reapportion - Hold Performance But Design to Cost

COST & WEIGHT MODELING ARE KEY PARALLEL EFFORTS
(continued)

When we evaluate the error budgets and their relationships to cost and weight, we work on both a "top-down" & "bottoms-up" basis, at evolving levels of system deconvolution. Initial top-down models might tie solely to top-level criteria such as diameter, F-number, wavefront error, F_N, segmentation method, and our active control arrangement. These early models also often rely heavily on historical data.

As the error budgets evolve, specific substrate and support structure materials are chosen and our top-down models are expanded to allow generic costs and weights to be refined. Eventually, the interplay between lower level error budget terms such as intercellular/interactuator deflection (as related to low/zero pressure polishing methods) and thermo-optically driven WFE (as tied to facesheet thicknesses, actuator spacings, and residual spatial frequencies) can be estimated. Finally, as the design evolves, bottoms-up estimates for cost and weight can be made for the specific components and hardware end-items of interest. Tables, such as the one shown, would be constructed to show how cost and weight vary over material type and as a function of both WFE and natural frequency.

COST & WEIGHT MODELING ARE KEY PARALLEL EFFORTS

(continued)

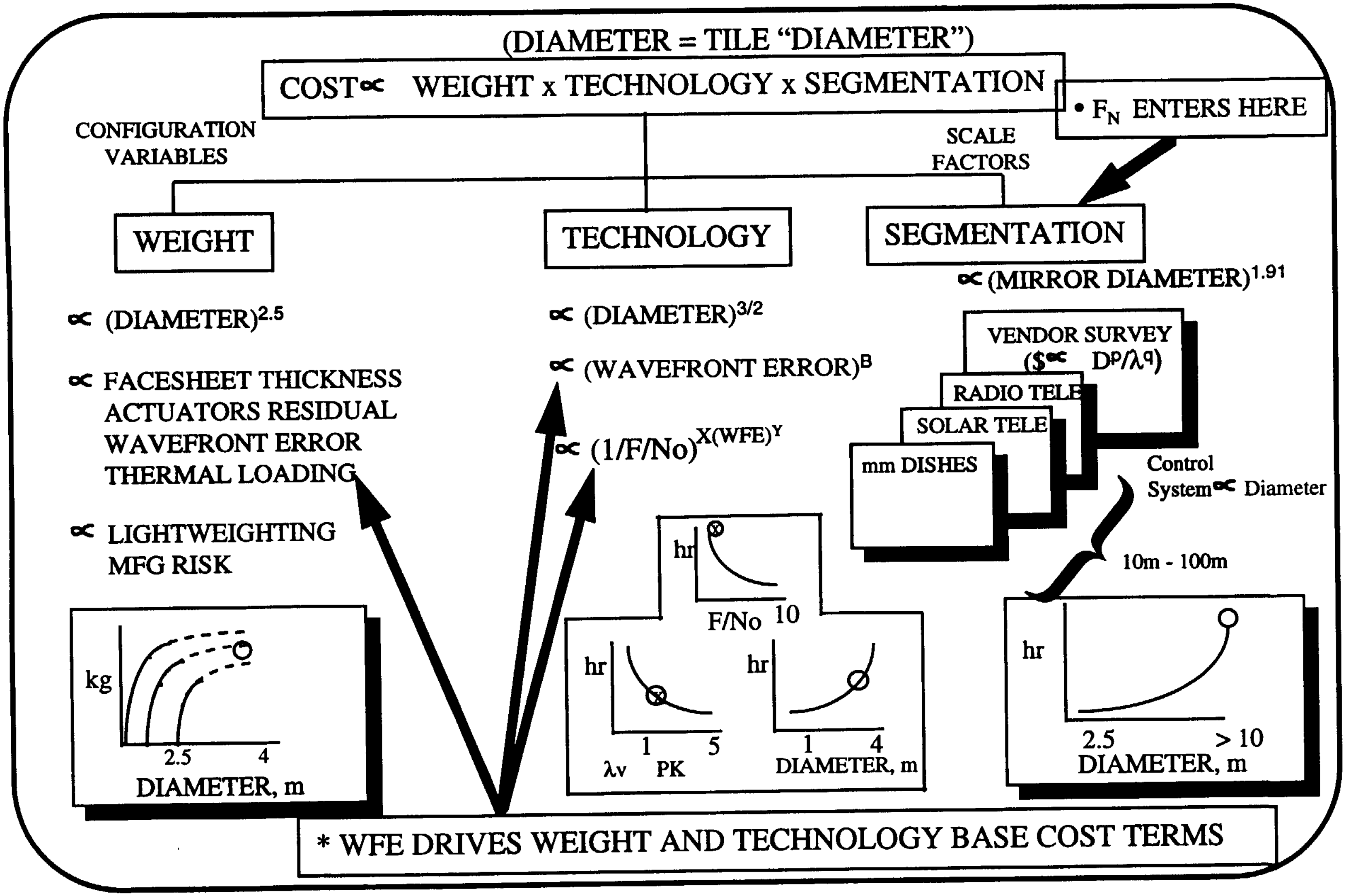
- Approach:
    - Both "Top-Down" & "Bottoms-Up" Methods are used
- Top Down:
    - Based on historical data
    - Over configuration variables
        - Deployed form; Active/Passive control
        - Mat'l-Be, Ni, SiC, Glass, G/E, Metal Matrix Composite
        - Intercellular Deflction (Ion Pol/"0" P/ thick surface)
        - Thermo-Optical (T/O) Errors Allowed
          Facesheet Th. vs # of Actuators
    - Bottoms-Up:
        - From first principles
        - Functionally, by Hardware End-Item

	13 [illegible]/X (19 TILES) (7.5[illegible] ULE, 0.015" [illegible], 20-10 [illegible])	
FACESHEET	COST	AREAL DENSITY
SUBSTRATE		
POLISHING		--------
COATING		--------
HOE'S		--------
FIGURE ACTUATORS		--------
REACTION STRUCTURE		
PHASING ACTUATORS		
SUPPORT STRUCTURE		
ASSEMBLY (1%)		--------
TEST (0.5%)		--------
MANAGEMENT (10%)		--------
TOTAL-PRIMARY		
LAUNCH-PRIMARY		
GRAND TOTAL-PRIMARY		--------

TOP DOWN COSTS TIE TO WEIGHT (&F_N), WFE, & SEGMENTATION

Some of the factors which relate to cost and weight are shown here. We have broken the various factors into three components. One component ties to system weight. At lower levels of system decomposition the relationships are much more complex (e.g., lighter can mean increased cost for various piece-parts). However, if we fit a many-termed equation with a simple overall relationship, we find that cost increases proportionally to overall weight, and that weight in turn ties to $(\text{tile-diameter})^{2.5}$, facesheet thickness (post actuator action for expected thermal loadings and as constrained by allowable WFE's), and lightweighting percentages (which ties to manufacturing risk). Cost (e.g., hours to make a specific optic) have also been found to tie to various technology factors that relate to material type, $(\text{diameter})^{3/2}$, $(\text{WFE})^B$, and $(1/\text{FNO})^C$ where $C = X(\text{WFE})^Y$. Further, costs tie to the way the deployed primary is segmented (e.g., this can go as $\text{diameter}^{1.91}$ for "super-LAMP" type arrangements), and the natural frequencies needed to achieve acceptable jitter and control-loop stability. Many systems have been surveyed in developing these ORA-proprietary relationships, from large optical telescopes, through mm-wave antennas, to large radio telescopes. Allowable WFE is the most important factor; it ties heavily to several weight and technology terms.

NGST
TOP DOWN COSTS TIE TO WEIGHT (& F_N), WFE, & SEGMENTATION



ORA'S MODELS TREAT KEY FACTORS/ALLOW COMPARISONS

Our models allow evaluation of various materials. A set of merit functions is shown in the upper left of the chart; these will be discussed further in subsequent charts. We also evaluate a wide range of fabrication factors and risks in establishing costs; some of these are shown in the upper right figure. Here ULE fused silica is shown; other data exist for alternate materials and construction methods, such as siliconized, reaction bonded, CVD, or reticulated foam versions of SiC, ceramic matrix composite material, Beryllium,etc.

In the lower left figure we see how our models can be used to help set an optimum tile size. As facesheet segment size climbs, overall mirror facesheet polishing costs drop. However, as facesheet reaction structure diameters rise, we lose support stiffness by (segment diameter)^4. We buy back this stiffness by increasing support depths by a cubic, causing the cost of the reaction structure to rise as segment size increases. This trade gives rise to an optimum segment size.

In 5-tier construction there is both a reaction structure (for actuators) and a lower support structure (for phase actuators) while in 3-tier construction a single reaction/support structure is employed (along with a set of dual-range actuators). This makes structure costs even more important in 5-tier construction, which shifts optimum tile sizes to smaller diameters. 5-tier construction can achieve higher levels of vibration isolation, but at higher net cost than 3-tier construction. Of course, doing our actuation on a smaller downstream mirror lowers cost still further and allows us to set the sizes more directly based on vendor costs and overhead and on deployment and packaging issues.

In the lower right we have plotted some generic curves for an actuated primary mirror where we need fewer actuators per segment for thinner effective mirror facesheets. Here RMS WFE is constant all along each curve, but cost and weight vary. Our first job will be to chose the appropriate actuator positions and segment/mirror geometry to produce a robust design of lowest possible cost (this is likely to benefit from downstream actuation).

NGST

ORA'S MODELS TREAT KEY FACTORS / ALLOW COMPARISONS

- Material Merit Functions

NO	CHARACTERISTICS	EQUATIONS	MERIT FUNCTIONS
5	SAG CHANGE DUE TO ΔTs (FIRST TERM – SAG CHANGE SECOND TERM – AXIAL STRAINS)	[illegible] $\frac{D^2 \Delta T_s}{8}$ WHERE R = MIRROR RADIUS $\Delta\alpha_{p-p}$ = AXIAL INHOMOGENEITY	$\frac{1}{\alpha} \frac{1}{\Delta\alpha_{p-p}}$
6	PK DEFLECTION (SELF WEIGHT) **	[illegible] WHERE ν = POISSON'S RATIO (SIMILAR FOR MOST MIRROR MATERIALS)	E (YOUNG'S MODULUS) / ρ
7	MICROYIELD STRESS, mYS (OR σ)	[illegible]	mYS / ρ

** AS PER PREVIOUS CHART

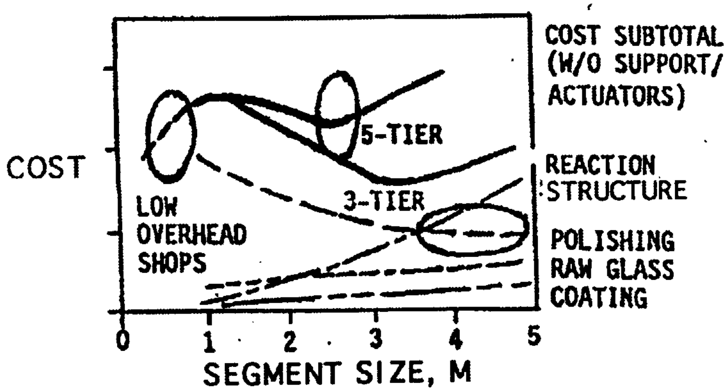
(ADDITIONAL FACTORS INCLUDE SCATTER, SCHEDULE, COST)

CoDRW3-7080/034MK

- Material Fabrication Factors

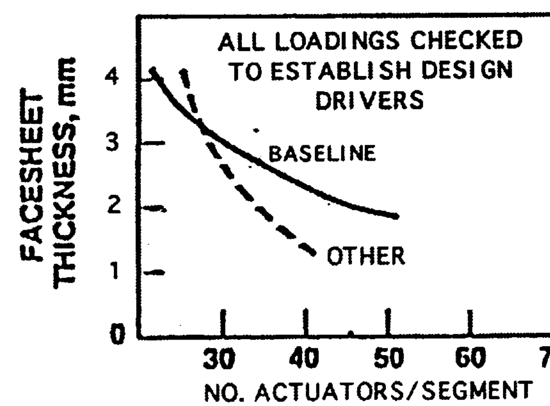
MATERIAL	ULE FUSED SILICA	SILICONIZED	REACTION BONDED	CHEMICAL VAPOR DEPOSITED	RETICULATED FOAM	CERAMIC MATRIX COMPOSITE
CONSTITUENTS	SiO_2, TiO_2					
MAX SIZE (m) Now / Future	4 / 8					
DEPOSITION RATE (in/hr)	[illegible]					
MOLD INACCURACY [illegible]	N/A					
GRINDING RATE (μm/hr)	30–50					
POLISHING RATE (μm/hr)	2					
ETCHING RATE (in/hr)	0.003					
FIGURE ACCURACY (RMS WFE, λ's)	0.01					
SUB-SURF DAMAGE (μm)	1–2					
DIAMOND TURN	[illegible]					
NO POLISH	YES					
SCATTER (Å)	<5					
CREEP (RMS WFE, λ's)	<0.01					
THERMO-OPTICAL CHANGES (RMS WFE, λ's)	[illegible]					

- As facesheet diameter increases, its cost drops, but reaction structure must deepen to hold stiffness (D^4/Th^3 relation) constant; this helps set best segment diameter



- Facesheet vs No. of actuators

(Curves of constant WFE, but costs vary along the curves; we choose design point to lower net cost consistent with other factors)

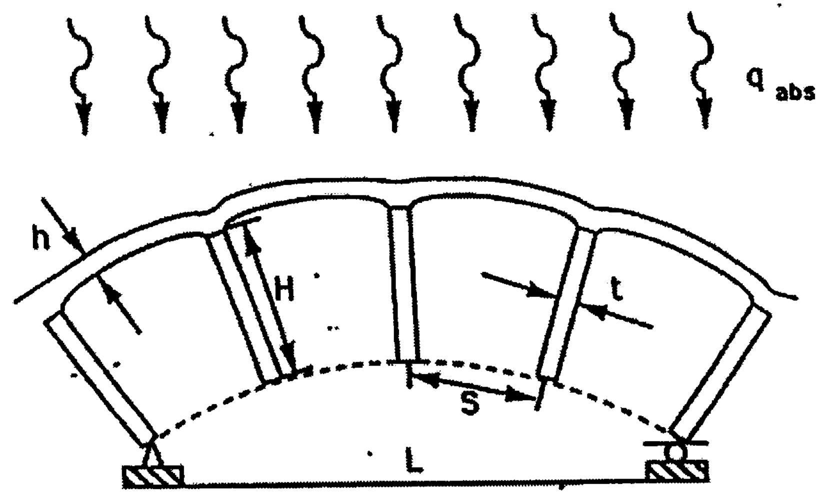


THERMO-OPTICAL (T/O) DISTORTIONS CAN BE A WFE DRIVER

This chart shows the effects of an input heat load (e.g., solar) on a lightweighted mirror facesheet. It is possible to tune the lightweight mirror's core emissivities and absorptions such that radiative exchanges through the core pockets are more nearly equivalent to conduction through facesheet web members, thereby equilibrating laterally varying axial temperature gradients. Of course these gradients also depend on various material properties (more on this later in upcoming charts), where somewhat different factors are more important during transient operation than at steady-state. Additionally, real-world factors such as substrate thermal expansion coefficient differentials (inhomogeneity) and mounting details are also critical in assessing net deformations.

The equators shown are for a free (or even simply-supported) facesheet and give overall mirror segment bow between supports (note that $h^1 = h + H$). These kinds of equations help us see what are the driving material properties and to construct material merit functions which directly tie to a simple first-order scoping of RMS WFE.

THERMO-OPTICAL (T/O) DISTORTIONS CAN BE A WFE DRIVER



- QUILTING RESULTS FROM THERMAL GRADIENTS THROUGH THE FACE SHEET
  - USUALLY SEVERE DURING TRANSIENT STATE
  - CAN BE NEGLIGIBLE FOR THIN FACE SHEET WITH HIGH CONDUCTIVITY MATERIAL
- OVERALL BOW RESULTS FROM THERMAL GRADIENT THROUGH FACE-SHEET-WEB DEPTH IN TRANSIENT AND STEADY STATE CONDITIONS

$$\delta = \frac{L^2}{8}\frac{\alpha}{k}q_{abs}$$

or

$$\delta = \frac{L^2}{8}\frac{\alpha \Delta T_G}{h'}$$

α = coeffient of thermal expansion

k = conductivity

q_{abs} = absorbed flux

ΔT_G = thermal gradient through thickness

h' = plate or mirror thickness

THERMO-OPTICAL MERIT FUNCTIONS, CONCLUDED

Merit function No. 5 gives overall mirror segment sag changes as driven by just plain uniform thermal expansion, as well as the effects of "bi-metallic" bending, as caused by any real-world, process-based axial expansion coefficient inhomogeneity of the material.

Merit function No. 6 gives G-release/self-weight deflections and resulting material factors of relevance.

Finally, merit function No. 7 gives factors that influence micro-yield (e.g., MKS stresses which result in 1 mm of permanent strain). These factors are more important in passive systems where adjustment/actuation is either not possible or is very limited, though they can also have relevance if they result in piece-part loosening during launch and subsequent control system chatter.

THERMO-OPTICAL MERIT FUNCTIONS, CONCLUDED

NO	CHARACTERISTICS	EQUATIONS	MERIT FUNCTIONS
5	SAG CHANGE DUE TO ΔT_S (FIRST TERM – SAG CHANGE SECOND TERM – AXIAL STRAINS)	$\omega_{SURF} \sim \left(\frac{\alpha}{R} + \frac{\Delta\alpha_{F-B}}{t}\right)\frac{D^2 \Delta T_S}{8}$ WHERE R = MIRROR RADIUS $\Delta\alpha_{F-B}$ = AXIAL INHOMOGENEITY	$\frac{1}{\alpha}, \frac{1}{\Delta\alpha_{F-B}}$
6	PK DEFLECTION (SELF WEIGHT) **	$\omega_{SURF} \approx \frac{\rho D^4 (5+\upsilon)(1-\upsilon)}{21.33\, E h^2}$ WHERE υ = POISSON'S RATIO (SIMILAR FOR MOST MIRROR MATERIALS)	$\frac{E \text{ (YOUNG'S MODULUS)}}{\rho}$
7	MICROYIELD STRESS, mYS (OR σ)	$\sigma \sim \frac{(3+\upsilon)\rho D^2}{10.67\, h}$	$\frac{mYS}{\rho}$

** AS PER PREVIOUS CHART

(ADDITIONAL FACTORS INCLUDE SCATTER, SCHEDULE, COST)

CoDR/K9-7080/024/MK

HIGH CONDUCTIVITY MATERIALS HAVE LOWER GRADIENTS BUT ALSO HAVE HIGHER EXPANSION & INHOMOGENEITY

Here we have taken some of the material properties noted in the preceding charts and listed the relevant data. Many materials are in evaluation, but only two are shown here for simplicity: ULE and SiC.

On the right we can see the influence of SiC's higher thermal conductivity; axial temperature gradients are reduced by ~100x.

HIGH CONDUCTIVITY MATERIALS HAVE LOWER GRADIENTS, BUT ALSO HAVE HIGHER EXPANSION & INHOMOGENEITY

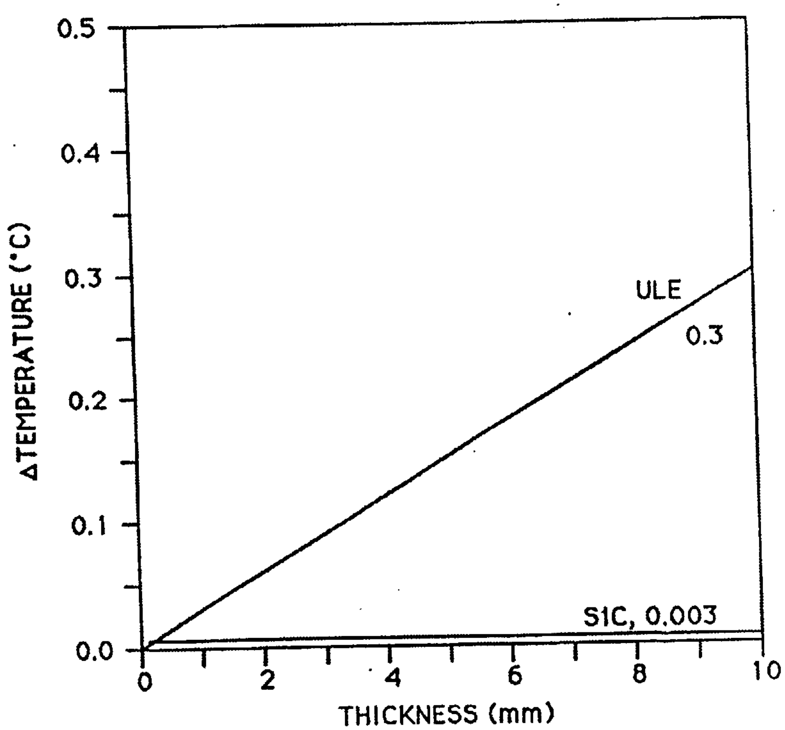
(300 K, 30 K TBD)

PARAMETER	SIC	ULE
ρ, DENSITY (LB/In^3)	0.080 [1]	0.080
E, YOUNG'S MODULUS (10^6 PSI)	56 [1]	9.8
α, THERMAL EXPANSION (PPM/°C)	3.5	0.03
$\Delta\alpha$, INHOMOGENEITY/ANISOTROPY (PPM/°C)	<0.05 [2]	0.015
k, THERMAL CONDUCTIVITY (W/cm -°K)	1.46 [3]	0.013
C_P, SPECIFIC HEAT (J/Kg-°K)	1420	766

[1] ESTIMATE FOR SIC/E-150

[2] LIMITED BY TEST ACCURACY

[3] FIBERS CAN CHANGE VALUE



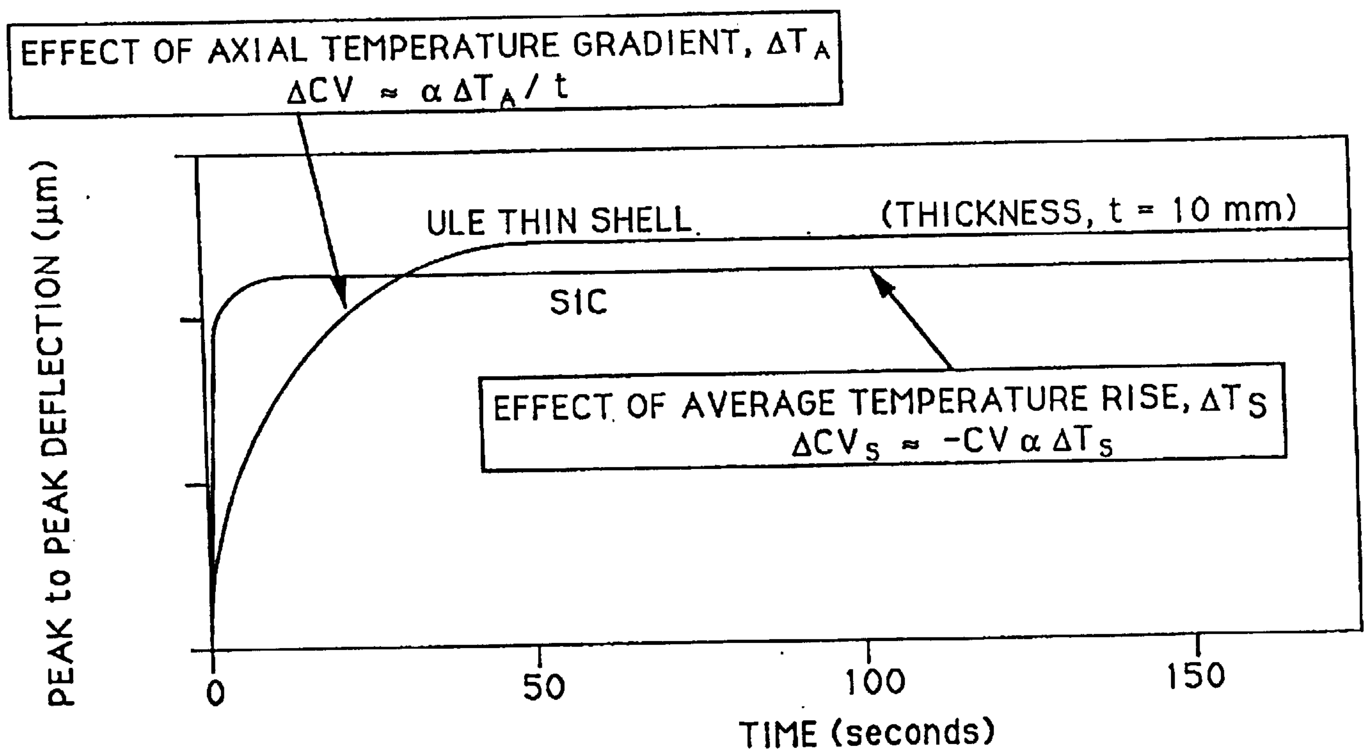
Other materials also available

SIC VS ULE AS A GENERIC BUT SPECIFIC COMPARISON

This figure basically shows the difference between merit function No. 1 (steady state where SiC, if homogeneous, shows lower errors), and merit function No. 3 (varying thermal environment, where ULE responds more slowly to the transient and has lower initial WFE). This comparison shows how solar residuals can influence the error budget, material choice, design of the actuator system (range, speed, etc.), and resulant specifications for acceptable thermal control. Since the influence of thermal errors is mitigated to a degree by the presence of active control, this is another area where the right cost optimization will need to be employed. Axial gradients can drive transient operation while thermal soak-derived scale changes can drive steady state conditions, though there *are* cross-product influences that can be significant, and issues of real-world piece-part homogeneity and mounting are also critical. Inhomogeneity can be especially important (dependent on thermal loading), as resultant surface errors at inconvenient spatial frequencies can contribute heavily to requirements for actuator number and spacing.

SIC vs ULE AS A GENERIC BUT SPECIFIC COMPARISON

- Effect of residual solar coupling through sunshade shown for a single petal
- SIC has advantage at steady state if homogeneous and isotropic, but actuators can need faster dynamic response if environment varies
- Conversely, ULE changes less quickly, but may have a somewhat larger net error to correct



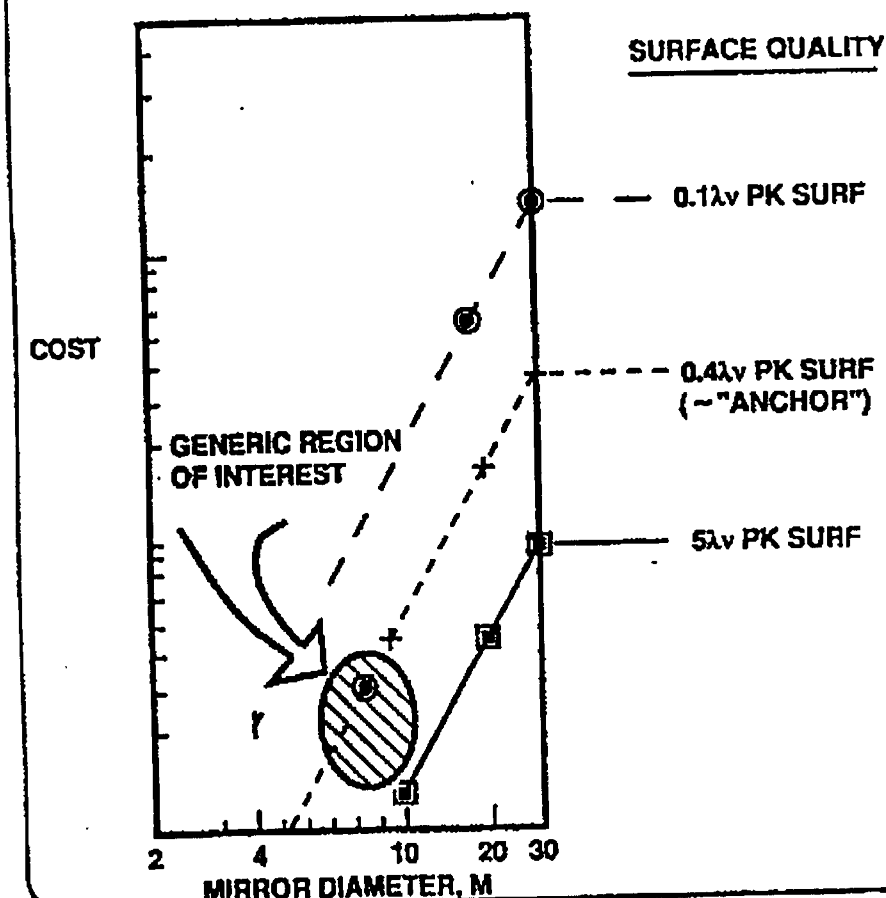
IMPACT OF ACTIVE CONTROL DEPENDENCE IS ASSESSABLE

We have used some of ORA's existing proprietary cost models to show generically how cost varies as a function of raw (pre-correction) WFE for various mirror sizes. On the left side of the figure we see that there can be a major (>10x) cost influence by configuring a system where pre-correction errors can be large - so long as the active control system can "clean-up" the wavefront.

On the right side of the chart we show a flow-down for a passive system, isolating terms which tie to higher spatial frequencies, i.e., those outside the capability of the correction loops. These are termssuch as intercellular or inter-support/actuator deflection, which can be caused by polishing residuals or axial temperature gradients. Since these terms are, by definition, outside the capability of the control loops, they also have high significance for final, on-station active system performance. As such they are design drivers, and need to be managed carefully to insure that errors are appropriately apportioned, so as to help drive configurations to those offering the lowest possible weight and cost.

IMPACT OF ACTIVE CONTROL DEPENDENCE IS ASSESSABLE

(TOP DOWN MODEL)



TYPICAL ERROR BUDGET FLOWDOWN

λ/15 RMS WFE @ λs

λ/50 HIGH SPATIAL FREQUENCY

λ/70 INTERCELLULAR DEFLECTION

λ/100 PRIMARY

= 0.1λv PK SURF

≈ 2.5 μ IN PK SURF

- ATTEMPT TO IDENTIFY DRIVING TERMS AND REAPPORTION TO MANAGE COST

CoDR/K9-7080/102/MK

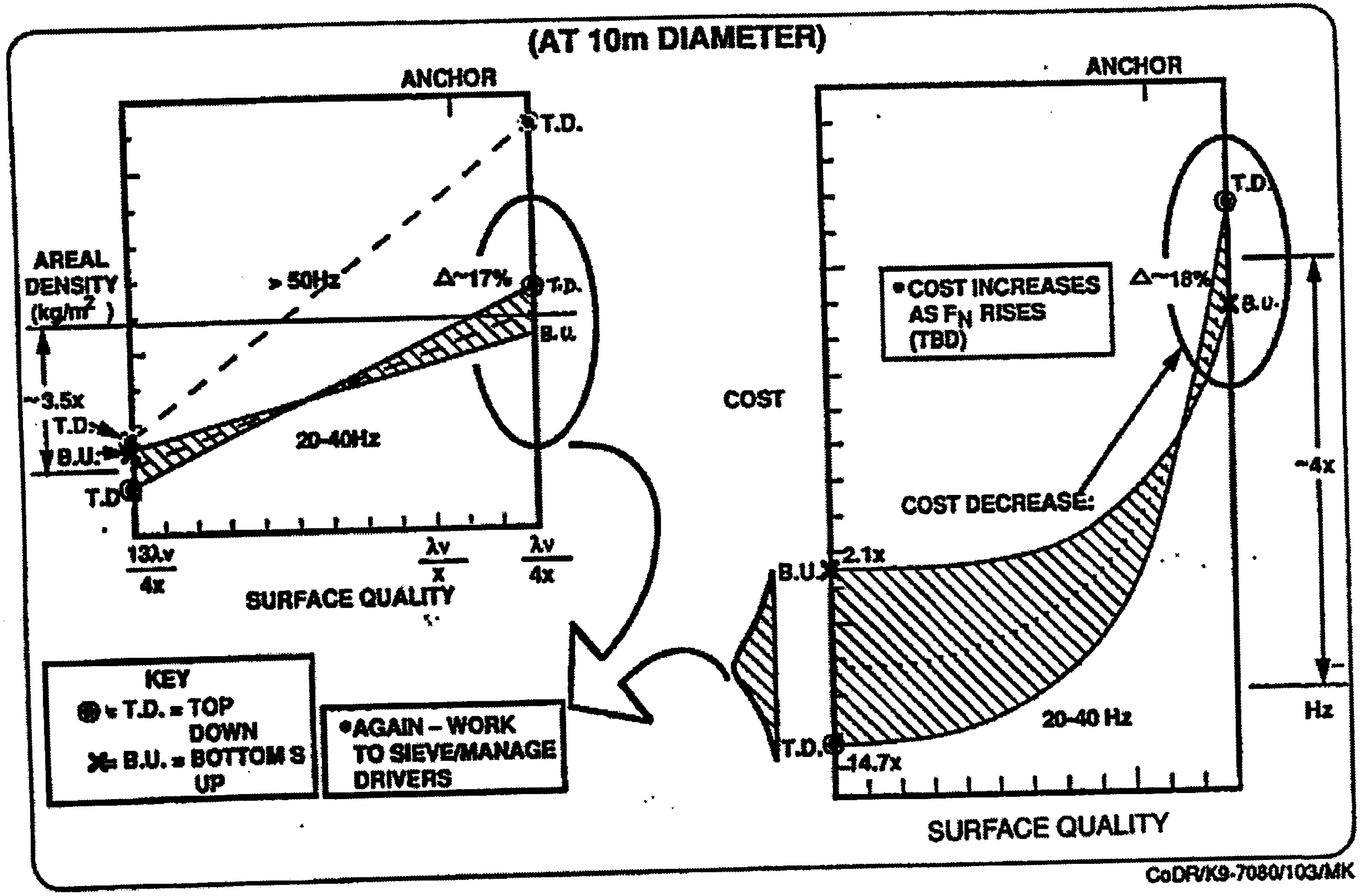
PARAMETRICS RUN ON BOTH WFE & NATURAL FREQUENCY

On the left we see how areal density can be lowered by ~3.5x by easing net WFE requirements by up to 13x (the horizontal axis; $x\lambda_S$ was our "base" and we first tightened tolerances from x to x/4, then loosened tolerances to 13x/4). We can also see how easing natural frequency requirements (~50Hz to 20Hz) lets us lower weights (the gain varies from ~2x for already eased WF conditions to ~5x at higher WF quality levels). These numbers are generic and depend upon many factors, but *are* illustrative and applicable.

On the right we have shown the "left-sides" lower (cross-hatched) set of curves (those for ~20-40Hz), but now for cost vs. quality (as opposed to areal density vs. quality). On average, costs drop ~4x (~2.1x to 14.7x, as a function of the model used) as quality is eased by ~13x. Models are most consistent at higher quality levels (18% variation).

These types of analysis should be continued to both refine the models at lower quality levels, refine WFE and natural frequency dependencies, and sieve/manage the design drivers for lowest possible weight and cost.

PARAMETRICS RUN ON BOTH WFE & NATURAL FREQUENCY



SO, WHAT'S THE ROM CONCLUSION(S) TODAY?

As we can see, the primary is obviously the cost/weight driver, with the facesheet the highest cost item, followed by the reaction/support structure, and the actuator/control system.

Weight (and cost) drivers are the design form itself, the segmentation pattern, WFE, natural frequency (where the reaction/support structure often limit control loop bandwidth which can be more or less important as a function of input disturbance levels/isolation), active/passive control method (actuators vs. phase conjugation) and location (at the primary and/or on a smaller downstream mirror at an image of the primary/pupil), material type (gauges and any lightweighting), intercellular/actuator deflections (ties to polishing loads/speeds and facesheet thicknesses), and thermo-optical errors (including characteristics such as substrate expansion homogeneity, coatings, thermal control methods, etc.).

Using the above factors and our model data, we conclude that a $10M, 8-m diameter primary mirror is a rational but very aggressive goal, while a weight of 10-12 kg/m^2 seems to be a 15%-30% stretch over a postulated and yet unachieved state-of-the-art.

SO, WHAT'S THE ROM CONCLUSION(S) TODAY?

BASED ON PRIOR PROGRAMS

- Primary ≈ 64% of weight (TBR) and ≈ 79% of cost
  - Primary mirror percentages (*Very* configuration dependent):

Example Shown with 4 Meter Panels & 3.0 Waves Pk Surf

• Faceplate -	43.5%	• Act Electronics -	6.1%
• Figure Actuators -	18.3%	• Gap Electronics -	4.7%
• React.Supt Struc -	24.3%	• Position Actuators -	3.1%

- Weight Drivers:
  - Design form, Segmentation, WFE, Nat freq. (React struct limits BW)
  - Active/Passive - Control method (Classic, Ph. Conjugation) / Location
  - $(\text{Diam})^{2.57}$
  - Material gage / Percent lightweighting (Thin solid face, TBR)
  - Intercellular deflection / Need to trade speed for cost (Preston's Law)
    - Polishing Load (<0.2 psi; Ion Polish; "0" Pressure Polish)
    - Facesheet thickness / Actuator spacing
  - Thermo-Optical Error (Substrate expan homogeneity/Actuator spacing)
    - Coating characteristics / Thermal control scheme
    - Facesheet thickness / Actuator spacing

TECHNOLOGY PROGRAM RECOMMENDATIONS

This chart summarizes our recommendations for technology activities that should be pursued to assure a low-to-moderate risk NGST flight system, launchable before the year 2010. In items 1 through 6, the intent is to provide for the development or demonstration of material or hardware configurations compatible with launch, cooldown and precision operation at 30K in a long-lived space system. In each case, the recommendation is based on extending the state of the art based on prior work supported by other Government programs, some of which were terminated when the associated defense requirement disappeared. Item 7 is included to support the choice between alternate technology approaches, and to support the overall system development by providing a framework for cost control and design optimization. Models may be used to assess performance of alternate technologies and to compare costs of the various approaches in a performance-based evaluation at any time within the development cycle.

Our preference is to employ and extend relatively low risk technologies, derived from the extensive work done on prior programs with which we are familiar. These would include such items as lightweight glass and SiC for the mirror facesheet, Graphite-epoxy or cyanate material for the composite mirror substrate and telescope structure, electrostrictive materials for precision actuators (especially in deformable pupil mirrors), and the hierarchical approach to system control. Each of these has been successfully employed in prior laboratory or field demonstrations at appropriate scale, and appears to require only a moderate amount of development attention to be useful for NGST flight hardware. Specific performance requirements and technology cost goals would be set as the program evolves.

TECHNOLOGY PROGRAM RECOMMENDATIONS

Area of OTA Need	Requirement	Time Frame GFY
1. Mirror Facesheet Material	Good figure at f/1.25, low mass	1997-8
2. Low Temperature Actuators Phasing, Figure	Operate for 10 yrs at low power, low weight	1997-9
3. Composite Mirror Assemblage	Achieve & hold phasing, figure	1998-2001
4. Deformable Pupil Mirror	Operate at useful bandwidth to 0.01λ	1997-9
5. System Control Architecture (incl pointing, WF control)	Control phasing, pointing, wavefront error under all disturbances	1997-2001
6. Deployment Mechanisms	Survive launch, deploy within control capture range	1997-2000
7. System Performance and Cost Modelling	Support tech choice/development and control system cost	1997-2003

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Leonard H. Solomon (SolVisions) and Mark Kahan (ORA)

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SolVisions
82 Albemarle Rd
Norwood, MA 02062

Optical Research Associates
East Coast Office
945 Concord St.
Framingham, MA 01701

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13. ABSTRACT *(Maximum 200 words)*

This report provides considerations and suggested approaches for design of the Optical Telescope Assembly and the segmented primary mirror of a Next Generation Space Telescope (NGST). Based on prior studies and hardware development, we provide data and design information on low-risk materials and hardware configurations most likely to meet low weight, low temperature and long-life requirements of the nominal 8-meter aperture NGST. We also provide preliminary data for cost and performance trades, and recommendations for technology development and demonstration required to support the system design effort.

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